Science Driven arguments for a 10 sq.meter, 1 arcsecond X-ray Telescope

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Abstract.

X-ray astronomy needs to set bold, science driven goals for the next decade. Only with defined science goals can we know what to work on, and a funding agency appreciate the need for significant technology developments. To be a forefront science the scale of advance must be 2 decades of sensitivity per decade of time. To be stable to new discoveries these should be general, discovery space, goals.

A detailed consideration of science goals leads us to propose that a mirror collecting area of 10 sq.meters with arcsecond resolution, good field of view (>10 arcmin), and with high spectral resolution spectroscopy (R=1000-10,000) defines the proper goal. This is about 100 times AXAF, or 30 times XMM. This workshop has shown that this goal is only a reasonable stretch from existing concepts, and may be insufficiently bold.

An investment of $\sim$\$ 10M/year for 5 years in X-ray optics technologies, comparable to NASA's investment in ASTRO-E or a SMEX, is needed, and would pay off hugely more than any small X-ray mission.

1. Long Term Goals for X-ray Astronomy

Any big undertaking, such as X-ray astronomy [1] surely is, must set long range goals. With clear long-term science goals in place we can see which developments are essential, and which are mere sidelines - amusing, but dead ends. Daniel Goldin, the NASA Administrator, urged astronomers (San Antonio AAS meeting, January 1996) to make decade length plans, even if the plan changes in a few years time. This is what we do here.

The goals we shall describe are deliberately ambitious. We propose that X-ray astronomers should aim to reach sensitivities 100 times beyond AXAF, while retaining high angular resolution and achieving high dispersion spectroscopy (Table 1) [2] . This does not mean that the very next mission we design should necessarily have all these capabilities. Nor does it rule out smaller missions with different goals. It does mean that the next major mission we design should at least be a deliberate and significant step toward these capabilities. To some

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[1] We discuss only the standard 0.1-10 keV band of X-ray astronomy, in which grazing incidence optics work efficiently.

[2] These numbers describe quite well Hale's Mt.Wilson 100-inch telescope (Osterbrock 1995), so we are suggesting that X-ray astronomy try to equal the state of optical astronomy in 1917.

readers these goals may seem hopelessly idealistic. As a result of this workshop, it seems instead that they are only a few factors of 2 away from reality.

In section 2 we outline several areas of wide astrophysical importance to which X-ray astronomy can make crucial measurements, given a 10 sq.meter,1 arc-sec. telescope ; in section 3 the current state of X-ray astronomy is reviewed and general 'discovery space' arguments are introduced; ; in section 4 we use these arguments to derive the 10 sq.meter, 1 arcsec, >10 arcmin field of view telescope goals; in section 5 we discuss instrumentation goals including the need for sensitivity in the 0.1-0.5 keV band; in section 6 we summarize our assessment of the workshop against these goals; and in section 7 we open the discussion on how to make this telescope a reality.

Table 1.   The 10 sq. meter X-ray Telescope

Large Area:	**10 sq. meters**
Good Angular Resolution:	**1 arcsec**
Wide Field Imaging:	**>10 arcmin**
Good Spectral Resolution:	**1000−10,000**

2.   Science Drivers

Where should X-ray astronomy be in the first decades of the 21st century? X-ray astronomy brings a unique potential for understanding the distant universe to astrophysics. Hot plasmas, matter under extreme conditions (density, temperature, pressure), and under intense gravitational fields, can only be directly observed in the X-ray band. These observations have implications for cosmology, the life cycle of matter, and relativity.

However, today X-ray astronomy can barely detect ordinary galaxies at the distance of Coma, clusters of galaxies at $z \sim 0.5$, and quasars at z=4 - all regimes where optical infrared and radio astronomy are flourishing. The X-ray missions to be launched in the late '90s will help. With AXAF and XMM, in typical 10^4s exposures, X-ray astronomers will be able to get a CCD spectrum with $R=E/\Delta E \sim 10\text{-}80$ (with ~ 1000 counts) for any source brighter than 10μCrab (the RASS limit), about 10^5 sources in the sky. This sounds powerful, but if optical telescopes were similarly limited to the brightest 10^5 objects they would stop at V=12, missing Pluto, the Crab pulsar, LMC cepheids (and hence the distance scale), and quasars altogether [3]. What is X-ray astronomy missing by not being able to sample a larger universe of objects? Even more limiting is the fact that AXAF and XMM have no more area for grating spectroscopy than the ROSAT PSPC had for imaging. Consequently, they will take $>10^6$s to get an $R=100$ spectrum (which is several times worse than even the most routine optical spectrum) of a 10μCrab X-ray source. What physics is being missed by lacking basic spectral diagnostics?

We have compiled a short list, covering topics ranging from cosmology to the solar system, of the obvious gaps that proposed missions cannot fill, but where a 10 sq.meter 1 arcsec. telescope will make crucial contributions. These topics

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[3]Contrast this with optical astronomy where 10^8 objects are accessible (to B=21, Jones et al., 1991).

Table 2.   Capabilities of a 10 sq. meter X-ray Telescope

Target	no. sources in sky[a]	flux(cgs)	$\mu Crab$	counts in 10^4s	Type of spectra[b]
Bright sources	3,000	2.10^{-12}	100	10^6	R=1000 abs'n 30×30CCD
ROSAT Sky Survey (RASS) limit **Baseline Flux, f**	100,000	2.10^{-13}	10	10^5	R=10,000 em. R=1000 abs. 10×10CCD
ROSAT medium survey	4 million	2.10^{-14}	1	10^4	R=1000 3×3**CCD**
ROSAT Deep Survey (1st NLXG)	30 million	2.10^{-15}	0.1	1000	CCD
AXAF Deep Survey	100 million	2.10^{-16}	0.01	100	colors
Fully Resolved CXRB?	100 million?	2.10^{-17}	0.001	10	detection

a. from ROSAT extragalactic logN-logS (0.3-2.4 keV band). Multiply by $\sim$3 for 2-10 keV (Inoue et al., 1996); b. R=E/ΔE=λ/$\Delta\lambda$.

are not of interest only to high energy astronomers, but are of wide-ranging astrophysical relevance. With telescopes of the right sensitivity (Table 2), X-ray astronomy will play a key role in unraveling the fundamental mysteries of the Universe.

Geometry of the Universe (H_0, q_0), and Large Scale Flows: X-ray astronomy provides unique methods of probing the geometry of the Universe. The 'baryon catastrophe' and the abundances of the hot intracluster medium (ICM) in high redshift clusters of galaxies are already indirect constraints on the cosmological model. The Sunyaev-Zeld'ovich effect is the most straightforward of the physics-based techniques for measuring H_0 and q_0. It combines X-ray and radio astronomy and can be used to large redshifts.

Purely X-ray observations can also be used to measure H_0 and q_0 in a direct way. This method employs the absorption lines produced by the ICM in the spectrum of a background quasar, plus the cluster emission measure (Krolik & Raymond, 1988). High angular resolution is needed to reduce the background in the quasar spectrum due to the cluster, and large collecting area to build a spectrum. Thousands of Abell clusters have quasars for which a $R = 1000$ spectrum can be obtained with a 10 m^2 X-ray telescope in 10^4s (1μCrab) so large numbers of accurate H_0 measurements can be made quickly. Their dispersion will map large scale motions. q_0 can be measured with z$>$0.2 clusters in a total of 10^6s.

Deep Surveys: The origin of the cosmic X-ray background (CXRB) has been the 'Holy Grail' of X-ray astronomy for over 30 years. It is time not only to solve this mystery definitively, but to go beyond it, to understand the nature of the CXRB creating sources. Two thirds of the CXRB is now resolved into point sources, mostly AGN. What is the remaining 1/3? Probably something new.

The increase in the logN-logS curve at faint fluxes (0.1μCrab, Hasinger et al 1993) seems to be made of 'Narrow Line X-ray Galaxies' (NLXG, Jones et al., 1996) of unknown nature. A 10m^2 X-ray telescope can obtain $R = 1000$ spectra of the brightest of this supposed new source population, which may be galaxies undergoing an early burst of star formation. In 10^4s a 10m^2 X-ray telescope with $1''$ resolution and a 30 arcmin dia. field of view can detect 1 nanoCrab (100 times fainter than ROSAT), and one 10^5s exposure will gather good $R = 10$ spectra of 200-600 of these sources (Table 2), allowing investigation of their nature. The $\sim$250 brightest sources will give X-ray redshifts directly from the Fe-K line, if they have Raymond-Smith like spectra, or are heavily obscured AGN. In 10^5s ROSAT Deep Survey sources will give R=1000 spectra.

The Intergalactic Medium: The IGM left over from galaxy formation was barely constrained in its properties until recently. The IGM has now been detected by HST and HUT (Jakobsen et al 1994, Davidsen et al., 1995); Lyman-α forest clouds have been recognized to fill large amounts of intergalactic space; and these same clouds are found to be 'polluted' by early metal production.

However the UV Helium features are hidden by Galactic absorption at low z. Only X-ray spectra allow the investigation of the evolution of the IGM down to the present. X-ray absorption features toward low z AGN will measure abundances in the local IGM, and map out its ionization state as a function of environment (Aldcroft et al., 1994). A 10sq.m X-ray telescope can sample thousands of lines of sight at $R = 1000$. Moreover, if deep surveys resolve 99% of the CXRB into discrete sources then the Ω allowed in a hot diffuse IGM can be well constrained from limits on its bremsstrahlung emission (Barcons & Fabian 1992).

Quasar Environments at z$\geq$4: At high redshift there is dramatic optical evidence (the 'alignment effect') that quasars and radio galaxies lie in a high density medium which probably has X-ray temperatures. Strong, highly polarized, Lyman-α emitting gas with knotty complex shapes is seen aligned with the radio structures and may mark sites of jet-induced star formation.

A 10 sq.meter X-ray telescope can image this hot medium down to $L_X = 3 \times 10^{43} erg\ s^{-1}$ in 10^4s at z=3 (0.01μCrab). The Lyman-α emission extends over only a few arcseconds (for any z$>$2 1 arcsec.$\sim$20 kpc), and central quasars are bright, so 1 arcsecond imaging is essential. Studying this medium in absorption against the luminous ($L_X \sim 10^{47} erg\ s^{-1}$) central quasar will give abundances and ionization state (and distances). $R = 1000$ X-ray spectra of many quasars will be obtainable to z$>$4.

Protogalaxies: X-ray spectroscopy adds new and unique capabilities to current optical/UV studies of non-luminous material seen toward quasars in absorption. The strongest of these absorbers are the damped Lyman-α systems which are likely to be the long-sought protogalaxies (Wolfe 1995). While common at high z they die out toward the present, presumably forming the galaxies we now see around us.

X-ray K-edges give virtually ionization independent measures of total column density and so accurate abundances (unlike the saturated optical/UV lines of individual ions) and ionization states (Madejski et al., 1995). X-ray absorption lines probe hot ISM states inaccessible to lower energy observations, and

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can be studied at 1000 times smaller column density than edges, opening up the lower column density 'metal line systems' that lie around more developed galaxies (Steidel et al., 1995). The quasars involved are faint (10μCrab) and so 10 sq.meters of X-ray collecting area are essential.

Masses of quasar black holes: ASCA has shown good evidence that broad Fe-K lines exist in AGN X-ray spectra. These surely originate close the the event horizon of the central black hole, probably from the inner edge of an accretion disk. These lines are broadened by Doppler shifts and by the General Relativistic redshift escaping from the hole's potential. These distortions allow us to study matter in strong gravity, and to measure the 'mass function' of quasar black holes through cosmic time. To determine a line profile needs $\sim$20 bins, each determined to $\sim$5%. A typical Fe-K line carries <5% of an AGN X-ray flux, so 10^5 counts are needed, and hence to extend this measurement to high redshift ($\leq 10\mu$Crab) an area of 10 sq.meters is essential. To employ reverberation mapping on bright AGN needs the same area.

Spectroscopy & Plasma diagnostics: The application of spectroscopy and atomic physics to astronomy transformed it into astrophysics. X-ray astronomy will likewise be transformed by high dispersion spectroscopy. New plasma diagnostic tools over a wide range of celestial objects - stellar coronae, SNR, the hot ISM of galaxies, the ICM of clusters, ionized absorbers in AGN - will become available. Spectroscopy also yields Doppler velocities. Table 3 lists a few applications.

Table 3.   *R=1000* Spectroscopy with the 10sq. meter X-ray Telescope

•Quasar environments at z>3 (via absorption spectra)
•Protogalaxy physics (via damped Ly-α absorbers)
•Existence and masses of quasar black holes
•Quasar black holes: strong gravity GR
•Quasar accretion flow doppler mapping
•Compact binary orbits, masses, environments
•Stellar winds: profiles, enrichment of ISM,
•Coronal tomography
•Chemical evolution in Galaxies/clusters to z=1
•SS433-like double-jet sources out to M51
•SN expansion velocities & abundances to Virgo.

The X-ray emission line spectrum is rich in plasma diagnostic capabilities: Electron density diagnostics are derived from the line ratios of forbidden (z) to intercombination (x,y) lines of the He-like ions.
Temperature diagnostics come from the ratio of dielectronic satellite lines to resonance lines through the Boltzmann factor. The ratio $(x + y + z)/w$, where w is the resonance line, is also temperature-sensitive.
Abundance derivations in a multitemperature plasma require a fully consistent analysis of the temperature distribution..

High spectral resolution ($R > 1000$) is essential for these diagnostics. Line blending is pervasive throughout the spectral region below 2 keV where the great majority of diagnostics lie. In solar spectra with $R = 400$, most of the bins contain contributions from half a dozen lines (McKenzie et al., 1980), making

unambiguous decomposition impossible. At $R = 1000$ the line blending eases considerably.

Little attention has been given to the potential of *really high resolution* spectra (R=10,000) in X-ray astronomy. At this resolution new physics becomes available, through the measurement of thermal widths and doppler motions (Table 4) At kT =1 keV, with ions and electrons in equipartition, a medium mass ion such as oxygen has a thermal velocity of $\sim$100 km/s. To measure this width requires a spectral resolution of $\sim$30 km/s, i.e. R=10,000. The inherent limit to X-ray spectral resolution due to thermal line widths only applies to thermal, not photoionized plasmas, and only cuts in for R >10,000 and kT>10 keV.

Table 4.   High Spectral Resolution (R=10,000) Spectroscopy

Thermal width Ion temperatures can be determined for each ion, so testing both whether the ions are isothermal, and whether they are in thermal equilibrium with the electron temperatures derived from bremsstrahlung.
Doppler Motions are often of order 100 km/s. In binary systems, stellar winds, spiral galaxies, and mergers of clusters of galaxies this is a good benchmark value. Line centroids can be measured to this level even with lower resolution spectra, but not if two different velocity components are blended, as is likely to be the case in many systems. SNR turbulent velocities could be measured out to the LMC, and binary Doppler shifts (and so masses) out to M 31.
Absorption Lines can come from really cold plasma, as low as 10 K in star forming molecular clouds. Narrow lines are best seen at high resolution. Absorption line cross-sections are of order 1000 times those of absorption edges. So absorption line studies open up a large range of absorbers to potential study: instead of $N_H \sim 10^{21}$ to detect oxygen we need only $N_H \sim 10^{18}$.
Photoionized plasmas create new opportunities at R=10,000. The thermal temperature of a photoionized plasma will be lower than that of the incoming radiation and so will have smaller, physically interesting, line widths. The higher line density emitted by photoionized plasmas also benefits from higher spectral resolution.

Galaxies: Galaxies are key objects for the study of cosmology, the life cycle of matter, and stellar evolution. X-ray observations allow the study of key components such as the hot ISM, evolved compact objects, and active nuclei, which are either impossible or hard to explore in other spectral bands. With these data we can measure the metal abundance in the hot ISM of galaxies and the surrounding cluster medium; when hot X-ray haloes are present we can measure galaxy masses (and baryonic content and thus set constraints on Ω); we can study the evolution of the gaseous component and thus learn about global evolution of galaxies and matter life cycle; we can gain crucial understanding of the formation and evolution of binary X-ray sources, and for the evolution of SN and SNR; we can explore the faintest active nuclei and understand their nature. Galaxy ecology - the study of the cycling of enriched materials from galaxies into their environment - is *inherently* an X-ray subject. Escape velocities from galaxies, when thermalized, are kilovolt X-ray temperatures.

AXAF and XMM provide too few photons for these faint objects, and XMM, with its >10 arcsec HPD, also lacks the resolution to cleanly separate individual sources and galaxy components, except in a handful of the nearest galaxies. In Table 5 we show the depth of study that a 10 sq.m. X-ray telescope allows. Detailed feasibilities come from Fabbiano (1989) and from table 2. Arcsecond

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resolution is needed to resolve individual sources out to Virgo, the nearest place with a sample of elliptical galaxies.

By looking at large samples of galaxies over a large lookback time ($z > 1$), we can study the evolution of global X-ray properties. We can obtain X-ray data on large well-selected samples, that can be compared with other wavelengths in statistical studies. With 1 arcsec HPD, confusion will not be a problem for the most distant (and therefore lower flux) galaxies (1 nanoCrab). Moreover, these galaxies will have 1-2 arcsec diameters and so will be easily picked out in deep survey fields. In 10^5s we can get colors for these faint galaxies ($m_B = 20 - 25$). More nearby objects will cover a larger area of sky, and therefore there will be interlopers. However, spectra can identify background QSOs, which can then be used to explore the cold/warm ISM, via their absorption features.

Broad energy coverage is needed for the study of galaxies, which encompass soft emission from a hot ISM and stars, 'medium range' emission from SNR and the soft components of some classes of X-ray binary, and hard emission from the high energy components of massive binaries and of active nuclei.

Table 5.   Galaxies

Distance	With A=10 sq.m. and t=10^4s we can achieve...
Local Group to 10 Mpc	-R=1000-10,000 spectra of individual bright sources ($L_X > 10^{37}$erg s^{-1} at 10Mpc;$L_X > 10^{35}$erg s^{-1} at M31 -R=10 (CCD) spectra and colors of fainter sources -1 arcsec HPD is needed to resolve sources -study uniform samples of galactic sources in different environments,$\rightarrow$ key factors in source evolution $\rightarrow$Study SS433 double-jet sources out to M51 $\rightarrow$Binary doppler shifts (and so masses) in M31 $\rightarrow$SNR turbulent velocities in LMC $\rightarrow$spatial and spectral properties of the hot ISM
D$\leq$Virgo ($\sim$20 Mpc)	- R=1000 spectra of all galaxies ($L_X > 10^{39}erg\ s^{-1}$) -spatially resolved spectra of galaxies ($L_X > 10^{40}erg\ s^{-1}$) $\rightarrow$ study temp., density structure, chemical composition, motions of hot ISM of E and S0 galaxies, measure masses $\rightarrow$Supernova expansion velocities & abundances to Virgo
D$\leq$Coma ($\sim$100 Mpc)	- R=1000 spectra of all galaxies ($L_X > 10^{40}erg\ s^{-1}$) (includes bright S, and large fraction of E and S0)
D$\leq$500 Mpc	- R=10 (CCD) spectra of all galaxies, $L_X > 10^{40}erg\ s^{-1}$
Z$\leq$1	bright E galaxies ($L_X > 10^{42}erg\ s^{-1}$) $\rightarrow$ chemical evolution of galaxy ISM
Z$\leq$2	-R=10 (CCD) spectra of: cD galaxies, groups ($L_X > 10^{43}erg\ s^{-1}$) - all clusters of galaxies - rich distant clusters of galaxies $\rightarrow$Chemical evolution of the intracluster medium $\rightarrow$Mass motions in cooling flows & clusters

Stellar Winds: Stellar mass loss is a major contributor to the chemical evolution of the galaxy, so direct determination of abundances from X-ray spectra in stellar winds is important. X-rays are especially good for abundance determinations.

At a spectral resolution of 1000, one can measure Doppler broadening and line profiles of X-ray lines emitted in the winds of OB stars (whose winds are believed to flow at speeds of 1,000 km sec^{-1}); such studies will thus be definitive for testing models in which the X-ray emission is thought to come from shocked wind material embedded in the outflows. The distribution of plasma at different temperatures, using spectral emission lines to derive emission measures, can be tomographically mapped using stellar rotation.

Solar System: Medium resolution spectra can use X-ray fluorescent lines to give chemical composition and ionization state of the magnetospheric material of Jupiter and Saturn. Comets were unexpectedly bright and common in the ROSAT Sky survey. Their chemical composition can be studied with high resolution X-ray spectroscopy.

All Sky Surveys: ROSAT has produced a sky survey with 10^5 sources in the soft X-ray band, and ABRIXAS will soon complement this with similar numbers in the hard band (Trümper, this workshop). Deeper surveys are highly desirable. A factor 100 more sources over the whole sky will complement well the current large area optical (Sloan DSS) and radio (NVSS, FIRST) surveys.

A 10 m^2 telescope could provide its own 'Schmidt Survey': Following the ROSAT model, a 6-month sky survey (for a $30'$ dia. field of view) would reach a limiting flux density of 0.2μCrab, equal to that of the ROSAT 'Lockman Hole' Deep Survey (Hasinger et al., 1993). This would produce some 10 million sources on the sky. This Sky Survey could, for example detect and resolve normal galaxies well beyond Coma, a volume 3000 times larger than the RASS; and gather CCD spectra of rare coronal stellar populations, i.e. objects in the low-luminosity tail ($\approx 10^{25}$ ergs s^{-}1) of stellar X-ray luminosity functions for low-mass stars. The essential need for high angular resolution X-ray surveys was shown by the ROSAT HRI detection of large numbers of T Tauri stars missed by optical surveys. This has important repercussions on our understanding of the stellar IMF (Feigelson 1996) and so on star formation theory and galaxy evolution models. The survey would also provide a definitive study of the change (if any) in stellar activity levels as stars become fully convective on the main sequence.

This survey would simultaneously produce a survey in the 2–10 keV band to 1μCrab, giving $\sim$4 million sources (assuming the Ginga fluctuations logN-logS normalization). Being relatively unaffected by absorption, both Galactic and within sources, this hard band survey would go deep into the source population invoked to explain the discrepancy between the ROSAT and ASCA $logN-logS$.

The Fe-K 6-7 keV band would be covered too, and with CCD (or better) resolution the Fe-K line could be detected down to 20μCrab for normal thermal sources. Extraordinary sources such as NGC 6552 which have 15% of their flux in the Fe-K line (Fukazawa et al 1994) would be picked out at 1μCrab.

Other types of surveys are also matched well to 10 sq.meters: 'Rapid Surveys' of large samples of objects are essential to building statistical samples, classification of objects, and discovery of novel phenomena. At 10μCrab a 10 sq.meter collecting area will take 1000 s to obtain a high quality CCD resolution spectrum. With minimised slew times, normal users can assemble samples of dozens of objects.

3. X-ray Astronomy Discovery Space

ROSAT and ASCA have produced a wealth of excellent new results (see reviews by Keith Mason and Andy Fabian in this workshop). However, in the excitement over detecting emission lines and resolving 2/3 of the cosmic X-ray background we, as a community, often lose sight of the basic weakness of X-ray astronomy compared with the UV, optical, infrared and radio astronomies [4]. By whichever conventional measure of telescope performance is chosen (Table 6) X-ray astronomy is about a factor of 100 behind: angular resolution, spectral resolution, collecting area. Worse, to a great degree the other astronomies have these better capabilities all at once, whereas our telescopes specialize in one or another.

Table 6.   X-ray compared with other Astronomies

X-ray	UV/optical/IR/radio
5 arcsec	0.1−1 arcsec
$E/\Delta E$ =1-50	$E/\Delta E = 1000-10,000$
A_{eff}=0.02 m^2	A_{eff}= 3−75 m^2
$N_{sources}$=10^5	$N_{sources}$=10^8

Being far behind the other astronomies would not matter so much if X-ray astronomy were catching up. There was a long period, from the birth of cosmic X-ray astronomy to the end of the *Einstein Observatory*, when X-ray astronomy advanced in sensitivity by a factor of 100 every 10 years, 2 decades per decade (Table 7)- from sounding rockets to satellites to grazing incidence imaging. In those heady years being the underdog coming from behind was exciting. We were catching up the optical astronomers. We felt that soon we would be true equals. It didn't happen.

Table 7.   X-ray Astronomy's Rate of Progress

Year	Detection Threshold (μCrab)	Factor Increase	Spectrum Threshold (μCrab)	Factor Increase	Missions
1966	100000	—	∼10,000,000 (solar flare)	—	rockets
1976	1000	100	1,000,000 (Bragg)	10	*Uhuru*,Ariel V SAS-3
1986	10	100	10,000 (grating)	100	*Einstein*
1996	1	10	1000	10	ROSAT, ASCA
2006	0.1	10	100 (CCD) 1000 (gratings, calorimeters)	10 10	AXAF, XMM ASTRO-E
2016	0.001	100	10	100	10 sq.meter

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[4]Only Gamma-ray astronomy is worse off, but it has just leapt 2 decades with CGRO, and plans to leap another two with its next mission.

Had AXAF been launched on schedule that pace would have been maintained. Political problems, budgetary restrictions and tragic accident all contributed to the delay of AXAF. But whatever the causes, the effect has been to reduce the pace of X-ray astronomy's progress to one decade per decade. While X-ray astronomy was on hold, the optical, UV and IR astronomies have had HST, Keck and IR-arrays come into being to revolutionize them. X-ray astronomy now is no longer catching up, it is merely not slipping behind.

While important science drivers (as in §2) must be presented to justify any new major scientific project, the real advantage of a factor of 100 leap are the discoveries that cannot be foreseen. When making leaps of sensitivity by two orders of magnitude or more the only type of argument that works is the "Discovery Space" (Harwit 1984) kind. We ask "In order to go a factor of 100 fainter and so open up new volumes of discovery space, what do we need for: area (to get enough counts)?; angular resolution (to cut down background, and to locate sources)? How many counts do we need to accumulate a good spectrum? This style of argument is highly robust against changes in models and even to new discoveries. We use it in this paper.

The May 1980 proposal to NASA for a Large Orbiting X-ray Telescope ('LOXT') [5] provides an excellent example of the kind of justification to use for 'factor of 100' missions. Justified on the basis of discovery space arguments the LOXT program resulted in a strong NASA X-ray optics and detector R& D program. A more recent example is that of the Next Generation Space Telescope 'NGST' [6]. With a long term goal in place the agency can understand why particular technologies need to be developed.

We must do the same in X-ray astronomy. X-ray astronomy goals must be bold and science driven. Our goals must capture the imagination of the astronomy community, of the funding agencies and the public. This should not be hard. X-ray astrophysics encompasses much of the galaxy evolution and

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[5]The Large Orbiting X-ray Telescope ('LOXT') was first proposed in May 1970 (Tucker & Giacconi 1985), before the launch of $UHURU$ (December 1970). Only 20 cosmic X-ray sources were then reliably known (Seward, February 1970), all based on $\sim$5 minute sub-orbital flights, most with 1 degree-like angular resolution. The faintest source was about 40 mCrab. In essence it combined AXAF and XMM, strapped together and co-pointing on a single satellite (a 1.2^m dia., 2 arcsec mirror; plus a $0.5m^2$, 10 arcsec mirror). At the time of the LOXT proposal (which was accepted by NASA) the construction of such telescopes was well beyond the level of demonstrated technology. Skylab would not fly for 3 more years, and it would have 0.3^m dia. and $\sim$20 arcsec imaging (see e.g. Belew and Stuhlinger 1973). Imaging X-ray detectors had not been developed. (Skylab used film). X-ray microchannel plate imagers were only a concept. However, the goal of a large grazing incidence imaging telescope provided the scientific motivation for both an optics and a detector program. The funding agency could see the overall goal spelled out, so it could appreciate why the scientists needed the technology development money.

[6] The report 'HST and Beyond' (1996, ed. A. Dressler) sets a bold goal to succeed HST based solely on science considerations: the construction of a 6-8 meter diameter infrared optimized telescope, diffraction limited at 2 μm (0.2 arcsec), with its primary mirror cooled to 30-50 K, preferably in Jupiter orbit, to reduce the zodiacal light background (the dust that emits the zodiacal light is cooler there). These goals are technologically ambitious. No-one knows how to carry them out, especially within a plausible budget. Yet this report has led this year to a new NASA program of several million dollars per year, directed at carrying out its prime recommendation.

galaxy ecology targeted by NGST, and adds the twin theme of exotic physics through black holes, neutron stars, supernovae and quasars.

To appeal to a broad astrophysics community a mission must be sensitive enough to reach the whole enormous range of objects that we know emit X-rays, not just specialist High Energy objects. It also means that it must make good observations of these objects in a few hours, else too few observations will be taken to sample the richness of the X-ray sky.

To accomplish this we must take orders of magnitude steps and open new discovery space. We must accelerate X-ray astronomy toward the capabilities of optical, UV and radio astronomy.

4. Deriving the Telescope Goal

4.1. A 10 Square Meter Collecting Area

We begin with the concept of the 'baseline observation'. Everything then scales from this. The baseline observation can be defined without reference to any specific target. It relies solely on discovery space arguments. The starting point is to ask what a *typical* observation should be. This has four parts: What flux source (f)? What exposure time (t)? What detection efficiency (e)? How many counts (N)? Putting these together defines the collecting area (A):

$$N \; = \; f \, . \, A \, . \, t \, . \, e \, / \; <h\nu>$$

f is determined by the type and number of sources one must reach; t is determined by how many observations/year one should carry out; and N is determined by the type of measurement one wants to make. ($<h\nu>$ is the mean photon energy.) Even if you disagree with our choice of $fAte$, this approach allows us to compare proposed missions quantitatively.

With this approach we derive a baseline area A=10 sq.m. This is derived from a baseline t=10^4s, N=10^5 counts, f=10μCrab, and e=1. A $10\mu Crab$ source gives about 1 count/s/square meter (in the ROSAT band). (For grating spectroscopy $e = 1/4$ applies and hence longer t). We assumed $<h\nu>$=1 keV. These baseline values are justified below.

Flux (f) baseline: 10μCrab The typical observation will be of a source at a flux level that allows a wide choice of object. This must be faint enough that all classes of X-ray emitter are accessible. We take the ROSAT All Sky Survey (RASS) flux limit of 10 μCrab since many classes of source appear in quantity near this flux. Examples include: high z quasars, comets (Dennerl et al., 1996), Shapley-Ames galaxies

Exposure (t) baseline: 10^4 s To have a healthy scientific discipline observers need to compete with one another; they need to follow-up on observations that are puzzling; or on observations that show promise. To support this the telescope needs to be able to observe a reasonable sized sample of each type of X-ray emitting object each year. Let us say there are 100 categories [7]. Then to make

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[7]This is clearly a somewhat arbitrary division, but the number is substantial. The old *Einstein Observatory* Catalog of observations (the "Yellow Book", Seward & Martenis 1986) already

20 observations in each category requires 2000 observations per year. There are 30 million seconds in a year. At 2/3 efficiency (a plausible, and simplifying value) an average observation has to last 10,000 s, i.e. 3 hours. That this is reasonable for serving a large community can be judged by a comparison with optical usage. Three hours would be considered a normal, somewhat long, exposure on a 4-meter class general user optical telescope [8].

Counts (N) baseline: 10^5 The number of counts we need in an observation depends on the type of data:

1. Spectroscopy The case for high resolution spectroscopy is well known in X-ray astronomy. The soft X-ray band contains a high density of atomic transitions that carry powerful diagnostic information about the plasma that creates them. Only spectroscopy can extract this information.

There is, though, no consensus on the resolution R needed. Typical values of 200-300 are usually talked of [9]. However solar spectra show that $R=1000$ is needed to remove 'line blending' confusion. and so have unambiguous temperature and density diagnostics.

The workhorse spectroscopic observation is likely to be an exploratory spectrum at $R = 1000$ [10] (Table 3). To translate a resolution into a number of counts we need signal-to-noise criteria. Emission line dominated spectra need about 20 counts/pixel on average. A bright line ($20\times$mean) will then be measured to about 5% , and a continuum point will be just detected with about 10 counts. Absorption line spectra need more counts, of order 100 counts/pixel, since the continuum must be accurately measured in each pixel so that narrow absorption

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contained about 50 categories. Since then the number has increased. 'Galaxies' for example were not separated into Ellipticals and Spirals, let alone 'hot gas dominated Ellipticals' vs. 'binary dominated Ellipticals'; 'Star formation' was only one category; comets were not mentioned; and so on.

[8] This also accords with the experience on ROSAT and ASCA. ROSAT made ∼1500 pointed observations per year with an average exposure of ∼10 ksec. ROSAT publications are running at 450 publications per year (Trümper, this workshop). The range of subjects addressed by PSPC observations spans all of X-ray astronomy (see Würzburg proceedings, Zimmermann, Trümper & Yorke, eds. 1996), and was used by many astronomers outside the main X-ray astronomy groups. ASCA instead observes about 250 targets per year with an average exposure of around 35 ksec, and publications are of order 60 per year. ASCA spans a more restricted range of topics (see Makino & Tanaka, eds. 1994) and, although in those fields its contributions are of great importance, ASCA is used overwhelmingly by 'hard core' X-ray astronomers from a small number of groups.

[9] A physical argument for the R required to remove blending can be based on the separation of the triplet and satellite lines for a given ion, indicating $R=300$ to be sufficient (Holt, these proceedings); this happens to be the thermodynamic limit of microcalorimeters. Real plasmas, however, contain multiple ions of each element and multiple elements. Moreover, astrophysics plasmas rarely have a single temperature, or density. Still worse, photoionized plasmas are common. These, in de-exciting from the high levels at which they recombine, find many more pathways to the ground state, and so produce quite different lines (Liedahl et al., 1990). In real astrophysical sources then, far more lines will be present than the 'triplet/satellite' argument suggests. Solar spectra at $R=400$ are heavily blended (McKenzie et al., 1980) and require at least R=1000 before the number of emission lines per resolution element drops to a few.

[10] About the resolution obtained in routine optical identification programs for X-ray sources.

lines can be individually significant. For $R=1000$ these criteria require $\sim 10^5$ and $\sim 10^6$ counts.

2. High Resolution Spectroscopy At this resolution new physics possibilities open up, such as Doppler motions and thermal widths (Table 4). For $R=10,000$ we need $\sim 10^6$ counts for emission line spectra.

3. Imaging spectroscopy This is demanding. A moderate quality CCD spectrum requires 1000 counts, so at 100eV resolution 10^5 counts allows us to extract 100 independent spectra from an image. This is quite limited, as can be seen if you imagine a 10×10 image of a face. At 10eV calorimeter resolution only 10 spectra can be filled. (Note that this argument is independent of how the spatial bins are chosen.) While line-dominated sources will fare better in the strong lines, 10^5 counts forms a minimal requirement.

4. Imaging: Dynamic Range*(brightest peak/faintest detected features)* Dynamic range determines image quality. Astronomy, being a logarithmic subject, needs large dynamic range. Faint features often reveal the physics. For example, the powering of radio galaxy lobes was puzzling before the VLA imaged the narrow plasma jets directed from the active nucleus to the lobes, many kpc distant. The VLA detected these jets not because of improved spatial resolution, but because of its much better dynamic range of $\sim$1000.

By comparison the best X-ray images from ROSAT have tiny dynamic range. The ROSAT Calendar picture of complex structure in the NGC 1275 cooling flow (Sept 1994, also Böhringer et al., 1994) has a dynamic range of only a few. (Excluding the nuclear point source.) If the faintest pixels have marginal, 10 photon, detections, then a dynamic range of 1000 requires 10^4 photons in the peak pixel. So 10^5 photons are needed in the source.

4.2. Angular Resolution: 1 arcsec. HPD

The second key parameter in any telescope design is angular resolution. The primary reason that we want high angular resolution is that astrophysical sources show structure on a the finest scale we have yet imaged. But this is a squishy standard. Fortunately there are some quantifiable criteria and these lead to quite high angular resolution requirements, half power diameters (HPD) of a few arcseconds [11]. We propose the angular resolution goal of 1 arcsecond HPD.

1. Detection Confusion The best known criterion is 'source confusion'. To avoid this problem radio astronomers developed a flux limit criterion for telescopes (Murdoch, Crawford & Jauncey, 1973). Essentially this is a Poisson statistics problem. If we adopt the criterion that *"A detection should due to only one source at the 3.5σ gaussian confidence level"* then the mean density of sources on the sky comes out to be 1 per 40 beams.

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[11] Proposals always quote a resolution and an effective area, but these two numbers are linked. For example when using a Half Power Diameter for spectroscopy, the effective area should be divided by two since half the counts (by definition) are outside the HPD. A more appropriate measure of resolution for spectroscopy would be the 80% PD, closer to the typical extraction region used in practice. But then the angular resolution of the mirror will be 2.5-5 times worse (using XMM as an example, Willingale, this workshop). We will scale all results to the HPD.

How this translates to a beamsize depends on knowing the logN-logS relation for the sources in question. From ROSAT we now have a good handle on this down to faint X-ray fluxes. Applying the 1 in 40 criterion then at the $1\mu Crab$ level ('ROSAT Medium Survey' level) we need a half power diameter (HPD) of 14 arcsec. For the hard 2-10 keV band, the higher logN-logS normalization (Inoue et al., 1996) brings this down to 8 arcsec. At the ROSAT Deep Survey limit ($0.1\mu Crab$) the HPDs come down to 4 arcsec and 2 arcsec respectively. At faint fluxes (0.1μCrab) extragalactic sources are not randomly distributed, but follow the large scale structure distributions of galaxies (Refregier et al., 1996), implying HPD<4 arcsec.

2. Spectral Confusion There is another type of confusion that is important even for 10μCrab (RASS limit) sources. If we saw an unexpected emission line at a strange energy in a source spectrum, we would need to have confidence that this was not due to a background or foreground contaminating source [12]. . Highly obscured AGN emit a reflection spectrum which is dominated by large equivalent width emission lines (e.g. the Circinus galaxy, Matt et al. 1996). Even if such a source were 20 times fainter than the target it would still produce strong lines (up to EW$\sim$100 eV). Such objects are likely major contributors to the population that produces the enhanced logN-logS above 2 keV, so they may be common. Foreground M stars (particularly during flares) are another source of spectral confusion. (Brief observations with higher resolution instruments won't detect the lines, so won't solve the problem.)

A strict criterion is needed when looking for peculiar features in individual objects. If we adopt the criterion that *"A detection should due to only one source at the 5σ gaussian confidence level"* then the mean density of sources on the sky comes out to be 1 per 1000 beams. Because of line dominated sources a source density of 200/sq.degree (i.e. for sources at least 20 times fainter than the baseline, $10\mu Crab$, target must be used, as well as an 80%HPD extraction region. [13]. This leads us to a HPD≤3 arcsec (≤2 arcsec above 2 keV).

3. Source Identification At $1\mu Crab$ ROSAT PSPC error circles (about 25 arcsec dia.) contain 2-3 optical candidates at 22^m (Jones et al., 1996). To identify the final 1/3 of the X-ray background we need to $\sim$1 nanoCrab, and so $m_r \sim$28.

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[12]The most famous recent example of this class of problem was the report of periodic variations in the Seyfert galaxy NGC 6814 (see Mittaz & Branduardi-Raymont, 1989, Done et al,. 1992). The short, stable period implied an accurate clock, ruling out all starburst AGN models, and strongly implying a black hole. Although only one AGN was involved it mattered hugely and for 5 years many papers were written chewing over the data and its interpretation. All for nought. In all observations prior to ROSAT another bright X-ray source, a galactic binary of the cataclysmic variable class, had been unknowingly included in the beam and had produced the periodicity (Madejski et al., 1994). (*Einstein* and EXOSAT-LE missed the CV because their field-of-view was too small.) NGC 6814 was a member of a sample of the Piccinotti et al., (1982) sample which was not source confused on the standard criterion by a factor of $\sim$5.

[13] Proposals always quote a resolution and an effective area, but these two numbers are linked. For example when using a Half Power Diameter for spectroscopy, the effective area should be divided by two since half the counts (by definition) are outside the HPD. A more appropriate measure of resolution for spectroscopy would be the 80% PD, closer to the typical extraction region used in practice. But then the angular resolution of the mirror will be 2.5-5 times worse (using XMM as an example, Willingale, this workshop). We will scale all results to the HPD.

At this level there is 1 galaxy per 4 arcsec dia. beam (Tyson, 1988). This then requires source centroiding to 2.5 arcsec to get a few percent chance coincidence rate. Since the faintest sources are always $\sim 3\sigma$ detections this implies a HPD<4 arcsec.

4. Background Reduction To reduce the background to 10% of the source counts at $10\mu Crab$ (RASS limit) level requires a $\sim 80\%$PD source extraction regionan HPD<20 arcsec.

5. Rich Fields There are many places where sources are not randomly distributed. Clusters of point sources are found in star formation regions, spiral galaxies, HII regions, starburst galaxies, globular clusters, and individual galaxies in clusters of galaxies (detectable to Coma with a 10 sq. m. telescope). In each case the HPD is reduced by (source density)$^{1/2}$, i.e. HPD<4 arcsec.

6. The Real Reason: Complex Structures The ROSAT HRI has shown us complex structures down to its 5 arcsec HPD in: Clusters of galaxies, active galaxies, elliptical and spiral galaxies, supernova remnants, globular clusters, star formation regions, and other places. (see Würzburg meeting proceedings, eds. Zimmermann, Trümper & Yorke 1996).

There is every reason to believe that we will continue to see complex structure with the 1 arcsec HPD of AXAF. We already know that UV, optical, near-IR and radio emitting objects have complex structures at the 1 arcsec level. The very same objects are X-ray sources. It is hard to imagine a general argument that says structure will be smooth in the X-ray band when it is complex at all longer wavelengths. Observing an inhomogeneous object with poor resolution can reveal averaged properties, but this is qualitatively inferior to seeing directly which temperature lies where and how they are juxtaposed. The minimum angular resolution goal should be 1 arcsec [14].

4.3. Field of View: >10 arcmin dia.

Since Wolter-like optics have a $\sim 1/2$ degree diameter field of view with good imaging, it is wasteful not to use it. Large fields of view enable: (1) serendipitous discoveries; (2) large area, even All-Sky, surveys; (3) accurate background subtraction; (4) large object imaging (Abell clusters, Shapley-Ames galaxies, star formation regions, and many others).

If all large objects and associations of objects had already been studied extensively, then a narrow field-of-view mission may make sense if, for example, a major mission simplification resulted. However, in X-ray astronomy we have not studied even the nearby objects yet in any detail (e.g. NGC 1275, above). Based on the sizes of nearby galaxies and clusters of galaxies, and the expected surface density of the faintest sources a field of view of at least 10 arcmin. is needed [15].

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[14] We should also not ignore the possibility of finer resolution. VLBI shows that milli-arcsecond structures can be seen in X-ray emitting objects, and micro-arcsecond resolution should resove binaries and AGN (Cash, this workshop). A long term investment into the feasibility of X-ray interferometry should be part of our program.

[15] A small field of view can be fine in some circumstances (e.g. WFPC-2 on HST). But even with a narrow field of view many independent pixels are usually needed. The trend in ground-based

5. Instrumentation Goals

We have derived from fundamental considerations that to enter the realm of capability enjoyed by the other astronomies, X-ray astronomy needs a mirror collecting area of 10 sq.meters focusing to 1 arcsecond. Spectroscopy at R=1000-10,000 is needed to exploit the richness of X-ray atomic physics.

There are some general points about the hardware for such a mission we need to make: (1) A major feature of a large area, good angular resolution X-ray telescope is the large variety of instruments to which it could fruitfully feed photons (see Table 8). Clearly large field imagers and high resolution (R >1000) spectrometers are both essential. (2) Grating spectroscopy is a major priority (see next point). (3) All instruments must have short (1 msec) readout times (4) The energy range for which the telescope is optimized should emphasize the lowest energy X-ray band (see below). (5) we should consider designs that allow an X-ray telescope to be upgraded with state-of-the-art instrumentation.

Table 8.   Instrumentation for the 10 sq.meter X-ray Telescope

Focal reducers/Re-imagers Large collecting area provides a tolerance for the loss of light extra reflections produce. Additional optical surfaces allow the whole gamut of traditional optics devices to be used for X-ray astronomy: collimators, re-imagers, focal reducers. These will have wide application in feeding new instruments.
Wide Field Imagers Wide field imagers are essential to surveys, and the study of extended objects. CCD spectral resolution is all that can be usefully employed to fill arrays (see Table 5, §5.3). Larger R, e.g. with cryogenic devices, is of course desirable. Re-imaging to a plate-scale optimized for existing detectors may be desirable.
R=**1000 Spectrographs** Basic X-ray plasma diagnostics become feasible only at R=1000 (see §5.3).
R=**10,000 Spectrographs** New physics (Doppler motions, thermal line widths) become accessible at R=10,000 (see §5.3).
Slit Spectrographs Current X-ray spectrometers are slitless. This leads to confusion and loss of resolution when observing crowded fields or extended sources. Many strong line emitting sources are extended (SNR, star forming regions, clusters of galaxies, galaxies) With collimating and re-imaging optics a true X-ray slit spectrograph could be built.
Spectral Re-imagers Komykhov lenses act like optical fibers in X-rays and are used in medical applications They are likely to be inefficient, but with enough photons they could be usefully employed to create a spectral-spatial data cube. A bundle of lenses could sample a 2-D image and re-image it into a linear array. This array could then be passed through a grating to form high resolution spectra.
Polarimeters Inherently hard since a $10\pm3\%$ measurement requires the count rate measured to $\pm0.3\%$, i.e. 10^6 counts. For 10% efficiency of polarization detection (e=0.1) this measurement can be carried out on a 100 μCrab source in 10 ksec.

5.1. Grating Spectroscopy

High resolution soft X-ray spectroscopy can only be carried out with dispersive techniques. Thus the current enthusiasm for cryogenic non-dispersive spectroscopy (see this workshop) needs some moderating. Microcalorimeters have

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telescopes instead is to create a multiplex advantage by building large field of view optics that can study hundreds of objects at once.

good points, in particular the clear factor of 3-4 QE gain over dispersive spectroscopic systems, and the prospect of an 'ideal' imaging spectroscopy detector. However they also have limitations:

(1) The resolution of a few hundred now in prospect from microcalorimeters will not be enough. Current microcalorimeters have a thermodynamic limit of 1-2 eV or about R=500 at 1 keV, and other noise sources may cut in before that limit is reached. The current best laboratory resolution is $\sim$5 eV, i.e. R=200 at 1 keV. To do better with non-dispersive methods does not yet seem feasible. (2) They have limited ($\sim 10 \times 10$) array size. Larger arrays require a long and expensive research and development program and may not be feasible (Cooper, this workshop). (3) They require complex blocking filters that limit low energy response. (4) They need ultra-low temperature cryogenics, which constrain satellite orbit (away from LEO), instrument lifetime, and increase instrument complexity and mass. Of course a new, perhaps even colder, class of non-dispersive instrument may come along.

Dispersive techniques are thus essential. This primarily means diffraction gratings. Dispersive grating spectroscopy is essential both for E<2 keV and for R ~10,000 spectroscopy. Fortunately, the price of going to dispersive spectroscopy is not excessive: a factor of 3-4 in efficiency (e), plus more complex optics to enable slit spectroscopy. Development of grating optics, especially for slit spectroscopy, must be a high priority.

5.2. The Softest Energy Band: 0.1-0.5 keV

The improvement in microcalorimeter resolution at higher energies is helping to drive the X-ray astronomy communities interests away from the sub-1 keV band. Much effort is going into extending the response of grazing incidence X-ray optics to the higher energy 10-50 keV band (e.g. Elvis, Fabricant and Gorenstein 1988, Gorenstein, this workshop).

The soft, 0.1–0.5 keV band has the same 0.7 decade bandwidth. as 10-50 keV and is scientifically far more important: (1) the soft band contains 10^4 times the number of photons (for a Crab spectrum), albeit dependent on Galactic absorption; (2) the soft band contains a huge number of atomic transitions as evidenced by solar spectra and EUVE; (3) as we observe to higher redshifts the familiar 0.5-2 keV lines and edges move into this band. By z=4, where many quasars are already known, the soft band has become 0.5-2 keV in the rest frame. However, a 2 eV microcalorimeter is reduced to R=100 at 0.2 keV. A grating spectrograph gains resolution at low energies and, using unfiltered detectors could be designed to work efficiently at R >1000 down to 0.1 keV.

6.   What did the Workshop Show?

The challenge of the goals set out above attracted many comments during the NGXO workshop. Somewhat to our surprise the goals do not look far-fetched. Optics technologies were described that approach (even exceeding) the goals.

Of the optics technologies discussed, microchannel plate optics are 100 times ligher per unit collecting area than replica optics and so will be valuable in large area 'light bucket' missions. However they seem unlikely to reach 1 arcsecond HPD (Fraser, this workshop) and so are not a candidate for the 10sq.meter

telescope. Foil optics seem unlikely to approach the necessary angular resolution (Serlemitsos, this workshop) and are 10 times heavier than microchannel plates per unit collecting area. Replica optics have a better chance to achieve one arcsecond (Willingale, this workshop).

More ambitious optics, such as the spherical multi-element systems described by Cash (these proceedings) or adaptation of the large optical telescope methodologies (e.g. Angel, private communication) have been little explored. These need development funding. Cash's spherical optics (Table 9, and this workshop) suggest that it may now be feasible to reach 0.1 arcsec imaging performance in X-ray astronomy.

Table 9.   X-ray Optics Technologies

Replica optics developed from XMM can be expected to reach HPD=5 arcsec, possibly 3 arcsec. With existing shell thicknesses Ariane V can lift 2-3 sq. m. into orbit (Willingale). Further lightweighting techniques might increase this by a factor of 2-3 (Citterio, Tananbaum). The angular resolution is still likely to be inadequate however.
Spherical optics seem to have major potential. To achieve <0.25 arcsec HPD at 8 keV on a first attempt is impressive. The low cost per unit collecting area is excellent. The error analysis showing that 1/100 arcsec HPD is plausible makes further development of these optics a top priority. If the sharp reduction in cost per kilogram to orbit being pursued by NASA comes to pass by 2005 as planned, then concerns about mirror weight will become less central. However, thinned optics designs must be worked on to get 10 sq.meters.
Large optical mirror technology has developed greatly in the last decade. Large light-weighted thin mirrors with good surface roughness have been built including a 2mm thick, 1m dia. prototype for NGST. Many of the techniques used at the Univ. of Arizona Mirror Lab., for example, could be adapted to the grazing incidence case (Angel R., private communication.)

A major weakness of the workshop was the lack of consideration of high spectral resolution using grating spectroscopy. Since this is the only route to the necessary goal of $R >$1000 spectroscopy, so we must pursue it.

Three main missions emerged from the workshop as the next step. However, they only partially address our goals. These missions overlap considerably in their aims and concept: (1) a European follow-on to XMM that takes replica mirror technology another step ($\sim$ 1-3m^2; $\leq$5" HPD); (2) a Japanese successor to ASTRO-E ($\sim$1 m^2, $\sim$30"[?]HPD) using improved foil optics, and launched with the new large H-2; and (3) the US 'High Throughput X-ray Spectroscopy' mission (HTXS) ($\sim$ 1m^2; $\leq$15" HPD).

In their collecting area these plans are only a factor of 5-10 too small. In angular resolution however they all are inadequate. Since all three missions stressed calorimeters and 10–50 keV response none reaches the spectral resolution and low energy coverage that will turn X-ray astronomy into X-ray astrophysics.

7.   What is to be done?

How can X-ray astronomy reach the 10 sq.m/1 arcsec goal? As a community we need to become less 'political' and more science driven. Presently we act tactically, reacting to each announcement of a mission opportunity by putting together good proposals. Since a good proposal requires the use of existing, proven technologies, we do not get beyond incremental advances. Instead we must get strategic. We must set long term science goals, as we have done here, and then *begin!* Start work now on achieving our goals through technology studies.

The primary thrust of these technology studies must be innovative X-ray optics: the pursuit of *several* new mirror technologies. These studies need substantial funding, of order $ 2M/year each (i.e. 5 man-years/year, including overhead, plus equipment). A $ 10M/year program sounds huge compared with the less than $ 0.5M/year now spent by NASA on X-ray optics, outside of flight programs. It is small potatoes, though compared with the astrophysics budget at NASA. It is similar to the NASA investment in ASTRO-E or a SMEX, yet the pay-off is hugely greater.

A second but still very important study must address the spacecraft and space infrastructure needed to support a 10 sq.m. high resolution telescope. Areas of importance include: long, low weight structures; active control of optical benches; moment-of-inertia balancing for fast slewing; servicing from Station, Shuttle and small launchers. Topical technical workshops on each of these areas would be a good way to focus the issues and technical challenges and to identify the most promising areas of work.

The US, European and Japanese intermediate missions presented at the workshop should not take all the energies of the community and so prevent a strong development program. The goal we originally outlined seemed bold. This workshop has shown that in fact it is quite plausible, and only a stretch from plans now being formulated.

To reach 10 sq. meters in 10 years (5 years of development and 5 years to build) brings us back on track to advancing the field by a factor of 100 per decade. Can we really do this? Only if we try.

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